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14. ABSTRACT
The project has successfully demonstrated reduced-rank, space-time equalization for high-speed wireless digital communications capable of reliably transmitting multimedia data in support of military operations in stressful environments involving multipath propagation. Research conducted as part of this effort was recognized by a number of awards including a Technical Achievement Award and a Distinguished Lecturer appointment from the IEEE Signal Processing Society, and two Best Paper Awards from the IEEE Communications Society. A key finding that fueled a number of innovations towards the end of the three-year effort was that adding a stage to the Multi-Stage Wiener Filter was exactly equivalent to taking a step of a Conjugate-Gradient (CG) search. A key innovation was the formulation of the matrix-vector product in the CG algorithm in terms of low-complexity FFT's for reduced computation and storage requirements. The results of this research was published extensively in a number of high-profile IEEE and SPIE conferences.

15. SUBJECT TERMS
Conjugate Gradients, Space-Time Processing, Adaptive Equalization; Intereference Cancelling

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Air Force Office of Scientific Research

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1 OBJECTIVES

The objectives were to identify, develop, evaluate, and demonstrate innovative space-time adaptive signal processing schemes for wireless communications that facilitate transmission of multimedia data during military operations by numerous users in the same geographical error utilizing a common spectrum. Wireless transmission of images and video requires high-speed digital data links over relatively broadbands with a high degree of frequency selectivity arising from multipath propagation in hilly or urban areas. Code Division Multiple Access (CDMA) is assumed as a result of the combination of the stressed multi-user nature of the digital battlefield and the requirement for low probability of intercept (LPI).

The major accomplishments centered on fundamental advances in reduced-rank adaptive filtering and their use in space-time equalization and interference cancellation algorithms for application to 3G+/4G MIMO wireless communication systems and Wireless LAN's. Reduced-rank processing, alternatively referred to more accurately as reduced dimension subspace processing, will be a vitally important element of future wireless communication systems, both near-term and far-term. This is due to the high dimensionality of equalizing weight vectors and/or interference cancelling weight vectors arising from a variety of factors:

1. at higher data speeds, the multipath delay spread spans a proportionately large number of data symbols thereby necessitating the use of more taps in a symbol-spaced equalizer

2. for MIMO communication systems, the dimensions of equalizing and/or interference cancelling weight vectors are directly scaled by the number of antennas at the transmitter and/or receiver

3. polarization is an additional discriminating feature for smart antennas that can be used to differentiate amongst co-channel users, enabling co-channel users closely-spaced in angle to be separated – all for the purpose of increased capacity. Again, though, judicious exploitation of a polarization diverse smart antenna increases weight vector dimensionality.

4. in short-code CDMA systems, Multi-User Access Interference (MAI) can be canceled in so-called code space, where the interference cancelling weight vector is at least as long as the code length, which can be high to achieve a large processing gain against noise.

2 STATUS OF EFFORT

A review of this project was conducted 6-8 June 2002 as part of the SIGNALS COMMUNICATION PROGRAM REVIEW AT THE UNIVERSITY OF VERMONT. The web site for this AFOSR meeting is http://www.njcwt.org/signalscommunication.html contains the slides that overview the key accomplishments of this project. In addition, an all-day tutorial on this work, entitled "TUTORIAL ON REDUCED-RANK ADAPTIVE FILTERING BASED ON THE MULTI-STAGE WIENER FILTER," was presented on 18 June 2002 to the CITE Group at Rome Labs headed by Dr. Bruce Suter.

Although the honors and awards information is presented in Section 8, key honors related to research conducted as part of this funded effort are highlighted below.

1. **2002 Technical Achievement Award of IEEE Signal Processing Society.** http://www.ieee.org/organ , "The Technical Achievement Award honors a person who, over a period of years, has made outstanding technical contributions to the theory and/or practice in technical areas within the scope of the Society, as demonstrated by publications, patents, or recognized impact on the field. The prize shall be $1500, a plaque and a certificate, and shall be presented at the ICASSP meeting held during the Spring following selection of the winner."

2. **Leonard G. Abraham Prize Paper Award in the Field of Communications Systems, IEEE Communications Society**, recipient along with Tai-Ann Chen, Wen-Yi Kuo, Jim Grimm, and Michael P. Fitz, for "A Space-Time Model for Frequency Nonselective Rayleigh Fading Channels with Applications to Space-Time Modems" appearing in the July 2000 issue of IEEE Journal on Selected Areas in Communications (Vol. 18, No. 7, pp. 1175-1190). Award presented at IEEE International Communications Conference (ICC) in Helsinki, Finland, on June 13, 2001. http://www.comsoc.org/socstr/awards/paperawards.html
http://www.comsoc.org/socstr/awards/paperawards.html#Leonard G. Abraham Prize

3. **2003 Distinguished Lecturer for IEEE Signal Processing Society.** There are six Distinguished Lecturers chosen each year to represent the Society by giving lectures on their research around the world. The web site for the SPS Distinguished Lecturer Program indicates that "The Society's Distinguished Lecturer Program provides means for chapters to have access to individuals who are well known educators and authors in the fields of signal processing, to lecture at Chapter meetings." http://www.ieee.org/organizations/society/sp/dlinfo.html

4. **Best Paper Award at IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA 2000)**, recipient along with Thomas P. Krauss, held in Parsippany, NJ, 6-8 September 2000. The paper was entitled "MMSE Equalization Under Conditions of Soft Hand-Off."

5. **Distinguished Lecturer** for *2002 IEEE Sensor Array and Multichannel (SAM) Workshop* in Rosslyn, VA, on 4-6 August 2002. One of 11 researchers invited to present Distinguished Lecture. http://ite.gmu.edu/sam2002/distinguished_lecturers.htm

Fundamental advances in reduced-rank adaptive filtering were developed for use in space-time equalization and interference cancellation algorithms for application to 3G+/4G MIMO wireless communication systems and Wireless LAN's. Reduced dimension subspace processing is vitally important for current and future high-speed military communication systems due to the large number of degrees of freedom and due to sample support issues related to receiver mobility and the nonstationarity of the mobile military communications environment.

Key accomplishments during the three year effort were fueled by our discovery of an inherent relationship between the MWF and the Iterative Search Method of Conjugate-Gradients (CG). This lead to a host of new algorithmic implementations of CG-MWF that offer a number of important advantages over the original implementation of MWF. The discovery that adding a"stage" to the MWF was equivalent to taking a "step" of a CG search has lead to substantial improvements to the MWF in terms of (i) computationally efficient implementations that exploit structure in the data matrices or correlation matrices, such as Toeplitz, sparseness, etc., (ii) amenability to real-time implementation, (iii) amenability to "smart" initialization (based on information learned or statistics estimated during the process of searching for a training sequence embedded in the data, for example), (iv) easy incorporation of a-priori information, constraints, and/or "past history" for accelerated convergence, and (v) amenability to complementary use of Principal Components of the data for further rank reduction.

Results obtained during the three-year research effort have been presented at and published in the proceedings of a number of high-profile conferences on communications and signal processing sponsored by the Institute of Electrical and Electronics Engineering (IEEE). A list of the papers either already presented and published, or accepted for presentation and publication during 2000-2002, is provided in Section 5.

3 ACCOMPLISHMENTS/NEW FINDINGS

The work centered on fundamental advances in the area of reduced-rank adaptive filtering, with particular emphasis on advancing the state-of-the-art of the Multi-Stage Nested Wiener Filter (MWF) originally developed by Goldstein, Reed, and Scharf. We made substantial gains in this area during the third year of this effort. Specifically, we have exploited our recent discovery of an inherent relationship between the MWF and the Iterative Search Method of Conjugate-Gradients (C-G) to formulate new algorithmic implementations of CG-MWF that offer a number of important advantages over the original implementation of MWF. In addition, CG-MWF offers a number of VIP advantages over both LMS and RLS based adaptive filtering as discussed below.

The basic implementation of CG-MWF for solving the $N \times N$ system of Wiener-Hopf equations $\mathbf{R}_{xx}\mathbf{w} = \mathbf{r}_{dx}$ is summarized in Table 1 on page 6, where $\mathbf{R}_{xx}$ is the covariance matrix of the observed data and $\mathbf{r}_{dx}$ is the cross-correlation vector between the desired signal and the observed data. For the beamforming application, $\mathbf{r}_{dx}$ is the steering vector for the current look direction.

Each step/iteration of CG-MWF involves two vector-vector multiplies, three simple vector updates, and one matrix-vector multiply. The latter is the most computationally burdensome step of CG-MWF. For Direct methods, the matrix $\mathbf{R}_{xx}$ is estimated from M blocks of data as $\mathbf{R}_{xx} = \mathbf{X}\mathbf{X}^H/M$, where $\mathbf{X}$ is an $N \times M$ Toeplitz data matrix. Through a novel circulant extension of a Toeplitz matrix " trick," we have shown that the product $\mathbf{R}_{xx}\mathbf{u}_i$ can be computed via FFT's leading to two VIP advantages: (1) substantially reduced computational complexity by choosing the FFT length to be a power of two and (2) substantially reduced memory requirements as $\mathbf{R}_{xx} = \mathbf{X}\mathbf{X}^H/M$ need not be formed and thus not stored. Relative to the latter point, all that is required is a one-time FFT of the data stream from which the M successive data blocks were extracted. Thus, in addition to the memory reduction, there is also the further computational reduction of not having to form $\mathbf{R}_{xx}$.

We presented the FFT based "fast" version of CG-MWF at the aforementioned Project Review on 8 June 2002 in Burlington, VT, and demonstrated its efficacy. Note that what we are talking about here is a new broad class of adaptive filtering algorithms that is as universally applicable as LMS and RLS. In fact, I believe it should be viewed as the next generation of adaptive filtering algorithms: first there was LMS and all its variations, then there was RLS and all its variations, and now there is CG-MWF with a number of variations.

As briefly described above, one of the major accomplishments of the first year effort was the development of an FFT based "fast" version of MWF that works at the covariance level (even though the covariance matrix need not be formed); there is no counterpart to this in the realm of RLS based algorithms. As part of the second year effort, we propose further refinements to CG-MWF that advantageously exploit the fact that it works directly on the covariance matrix. In contrast, RLS either explicitly or implicitly works with the inverse of the covariance matrix. As a result of the nonlinear relationship between the covariance matrix and its inverse, the innovations we propose have no counterpart in the realm of RLS based algorithms. As a result, in addition to the huge advantage of CG-MWF over RLS under conditions of low sample support, due to the inherent reduced-rank processing of CG-MWF, there are also huge advantages in terms of initialization and computational complexity as well. The computational complexity reduction of CG-MWF relative to RLS arises primarily from the ability to exploit the Toeplitz structure of the covariance matrix via FFT's. Since the inverse of a Toeplitz matrix is not Toeplitz (in general), RLS does not offer this feature.

Another key advantageous feature of CG-MWF relative to RLS is "smart initialization." In the equalization problem for wireless communications, for example, one may obtain an initial estimate of the impulse response of the propagation channel through semi-blind means (limited training plus exploitation of signal properties.) We say "initial", since the channel is time-varying, in general. The initial channel estimate may be used to initialize the covariance matrix, $\mathbf{R}_{xx}$, in the CG-MWF algorithm, as well as the cross-correlation vector, $\mathbf{r}_{dx}$. The former is the outer product of the convolution matrix of the channel with itself, while the latter is is the channel itself with some zero padding. Then both quantities can be updated on a per snapshot basis as time evolves to implicitly track the

time-variations of the channel. Preliminary results indicate that this channel based initialization of CG-MWF, which is possible due to the fact that CG-MWF works directly with $\mathbf{R}_{xx}$, has a very dramatic effect on the convergence speed of CG-MWF. In contrast, even if an estimate of the channel is available, there is no way for RLS to effectively utilize it since that would require inverting the outer product of the convolution matrix of the channel with itself, which totally defeats the purpose of RLS in addition to representing a huge attendant computational burden.

3.1 Key Advantageous Features of CG-MWF Reduced Rank Adaptive Filtering

As indicated previously, a key recent discovery is that the iterative search method of Conjugate Gradients (CG) is mathematically equivalent to the powerful and highly promising reduced rank adaptive filtering scheme called the Multi-Stage Wiener Filter (MWF) developed by Goldstein and Reed. This was a breakthrough since the MWF requires addition (or subtraction) of "stages" to the MWF on the fly in the form of a basic lattice module. Thus, for certain applications, the structure of the MWF is awkward to implement in real-time. The discovery that adding a"stage" to the MWF was equivalent to taking a "step" of a CG search has lead to a host of substantial improvements to the MWF in terms of

1. computationally efficient implementations that exploit structure in the data matrices or correlation matrices, such as Toeplitz, sparseness, etc.
2. amenability to real-time implementation
3. amenability to "smart" initialization (based on information learned or statistics estimated during the process of searching for a training sequence embedded in the data, for example)
4. easy incorporation of a-priori information, constraints, and/or "past history" for accelerated convergence
5. amenability to complementary use of Principal Components of the data for further rank reduction

Here we provide a brief explanation of Conjugate Gradient (CG) based reduced-rank adaptive filtering. The solution to the (Linear) Minimum Mean Square Estimation (MMSE) problem may be computed as the solution to the Wiener-Hopf equations, $\mathbf{R}_{xx}\mathbf{w} = \mathbf{r}_{dx}$, where $\mathbf{w}$ is the $N \times 1$ weight vector, $\mathbf{R}_{xx}$ is the $N \times N$ autocorrelation matrix of the data, and $\mathbf{r}_{dx}$ is the $N \times 1$ cross-correlation vector between the data and the desired signal. With sample data, we solve $\hat{\mathbf{R}}_{xx}\mathbf{w} = \hat{\mathbf{r}}_{dx}$, where $\hat{\mathbf{R}}_{xx}$ and $\hat{\mathbf{r}}_{dx}$ are estimates formed from the data and a training signal.

The method of Conjugate Gradients (CG) may be used to to solve the Wiener-Hopf equations. Since the MMSE problem is a quadratic optimization problem in N-dimensional space, a nice feature of CG-MWF is that it is guaranteed to find the solution to $\hat{\mathbf{R}}_{xx}\mathbf{w} = \hat{\mathbf{r}}_{dx}$ in N steps. However, what we find is that only a relatively few number of steps of CG-MWF is needed to obtain a close approximation to the solution, even when N is large. **More importantly**, though, when the sample support for estimating $\mathbf{R}_{xx}$ and $\mathbf{r}_{dx}$ is not adequate, as when N is large and/or the underlying signal statistics are varying rapidly due to mobility, taking additional steps of CG-MWF beyond a relatively small fraction of N actually degrades performance in terms of increasing the Mean Square Error!! Thus, reinforcing an assertion made previously, a small number of CG-MWF steps yields low computational complexity as well as improved performance. Even when the sample support is very low, a small number of steps of CG-MWF can yield a performance that is within a couple of dB of the performance obtained with the ideal (asymptotic) values of $\mathbf{R}_{xx}$ and $\mathbf{r}_{dx}$. The reason that this is tantamount to reduced-rank adaptive filtering is that taking $K < N$ steps of CG-MWF constrains the $N \times 1$ weight vector, $\mathbf{w}$, to lie in the following K dimensional Krylov subspace of N dimensional space: $\text{span}\{\hat{\mathbf{r}}_{dx}, \hat{\mathbf{R}}_{xx}\hat{\mathbf{r}}_{dx}, \hat{\mathbf{R}}_{xx}^2\hat{\mathbf{r}}_{dx}, ..., \hat{\mathbf{R}}_{xx}^{K-1}\hat{\mathbf{r}}_{dx}\}$.

3.2 Amenability of CG-MWF to "Smart" Initialization

Another important advantageous feature of CG-MWF relative to RLS (or LMS, for that matter) is the ability of CG-MWF to easily incorporate "smart" initialization. Equalization of 8-VSB Digital TV will serve as a motivating application for this discussion. In the 8-VSB standard, a periodic training sequence of length 704 (a PN sequence of length 511 followed by three concatenated PN sequences of length 63, plus 4 known sync symbols) is inserted into each frame of 230,000 symbols. During cold start-up, a running correlation with this 704 length training sequence is conducted to search for its location (within a frame) within the received (multipath distorted) data stream. The way that an LMS or RLS based equalizer would operate is that either would be trained starting from scratch after the training sequence is detected. However, in the vicinity of where the training sequence was detected in the received data, a pretty good estimate of the channel impulse response may be extracted from the running correlator output. Thus, an initial estimate of $\mathbf{R}_{xx}$ may be formed from this channel estimate as $\hat{\mathbf{R}}_{xx} = \hat{\mathcal{H}}\hat{\mathcal{H}}^H + \sigma_n^2\mathbf{I}$, where $\hat{\mathcal{H}}$ is convolution matrix formed from the channel estimate. Similarly, an initial estimate of $\mathbf{r}_{dx}$ may be formed from the channel estimate as $\hat{\mathcal{H}}\boldsymbol{\delta}_d$, where $\boldsymbol{\delta}_d$ is a vector of all zeroes except for a one in a single position corresponding to the equalizer delay.

As shown in Table 1, the initial estimates of $\mathbf{R}_{xx}$ and $\mathbf{r}_{dx}$, based on the channel estimate formed from some simple signal processing of the running correlator output, may be used to initialize Direct CG-MWF – not to initialize the equalizing weight vector, but to initialize the matrix $\mathbf{R}_{xx}$ and the vector $\mathbf{r}_{dx}$, which can then be updated on a per snapshot basis as time evolves to adaptively track time-variations of the channel. Simulation results to be presented shortly indicate that this channel based initialization of CG, which is possible due to the fact that CG-MWF works directly with $\mathbf{R}_{xx}$, has a very dramatic effect on the convergence speed of CG. In contrast, even if an estimate of the channel is available, there is no way for RLS to effectively utilize it since RLS either implicitly or explicitly updates $\mathbf{R}_{xx}^{-1}$ recursively. Thus, to use this information, we would have to initialize the inverse of $\mathbf{R}_{xx}$ to the inverse of the outer product of the convolution matrix of the channel with itself. Such a computation totally defeats the purpose of RLS and represents a huge computational burden as well (when N is large).

We demonstrate the power of "smart" initialization in a CG-MWF based Decision Feedback Equalizer (DFE).

3.3 CG-MWF Applied to DFE

The Wiener-Hopf equations for a Decision Feedback Equalizer may be expressed as

$$\begin{bmatrix} \mathbf{R}_{yy} & \mathbf{R}_{ys} \\ \mathbf{R}_{ys}^H & \mathbf{R}_{ss} \end{bmatrix} \begin{bmatrix} \mathbf{g}_F \\ \mathbf{g}_B \end{bmatrix} = \begin{bmatrix} \mathbf{r}_{dy} \\ \mathbf{r}_{ds} \end{bmatrix},$$

where the various component matrices may be expressed in terms of the channel convolution matrix as follows.

$$\begin{aligned} \mathbf{r}_{dy} &= \sigma_s^2 \mathcal{H}\boldsymbol{\delta}_D \\ \mathbf{R}_{yy} &= \sigma_s^2 \mathcal{H}\mathcal{H}^H + N_0\mathbf{I}_{N_F} \\ \mathbf{R}_{ys} &= \sigma_s^2 \mathcal{H}\boldsymbol{\Delta}_K \\ \mathbf{R}_{ss} &= \sigma_s^2 \mathbf{I}_{N_B} \\ \mathbf{r}_{ds} &= \mathbf{0} \end{aligned}$$

$\mathbf{g}_F$ contains the N_F feedforward tap values of the DFE, while $\mathbf{g}_B$ contains the N_B feedback tap values.

DFE based equalization of Digital TV is an ideal application for CG since the typical number of feed-forward taps, N_F, is around 200 while the number of feedback taps, N_B, is around 450 to

combat the large delay spreads encountered at UHF frequencies. (At a 10.76 MHz symbol rate, a delay spread of 45 microseconds encompasses roughly 450 symbols.) Thus, DFE for Digital TV represents a situation where the number of training symbols (704) is roughly equal to the dimension of the (feedback plus feedforward) equalizing weight vector. This is exactly the case where reduced-rank processing can yield substantial performance improvements over full-rank processing. In addition, CG-MWF based reduced-rank processing can make use of an initial channel estimate to initialize all matrices comprising the Wiener-Hopf equations as per the prescription above. The efficacy of this is demonstrated in the following simulation example.

The parameters characterizing the four channels employed in DFE for Digital TV equalization simulation are listed in Table 2 on the next page. There were 128 feedforward taps and 448 feedback taps.

$\hat{\mathbf{r}}_{dx}[0] = \hat{\mathcal{H}}\delta_d$
$\hat{\mathbf{R}}_{xx}[0] = \hat{\mathcal{H}}\hat{\mathcal{H}}^H + \hat{\sigma}_n^2\mathbf{I}$
for $n = 1, ..., N$ $\hat{\mathbf{R}}_{xx}[n] = \{(n + k_w)\hat{\mathbf{R}}_{xx}[n-1] +$ $\mathbf{x}[n]\mathbf{x}^H[n]\}/(n + k_w + 1)$
$\hat{\mathbf{r}}_{dx}[n] = \{(n + k_w)\hat{\mathbf{r}}_{dx}[n-1] +$ $d^*[n]\mathbf{x}[n]\}/(n + k_w + 1)$
$\mathbf{w}_0[n] = \mathbf{w}_D[n-1]$
$\mathbf{u}_1[n] = \mathbf{u}_D[n-1]$
for $i = 1, \ldots, D$ (typ. $D = 1$)
$\mathbf{v}[n] = \hat{\mathbf{R}}_{xx}[n]\mathbf{u}_i[n]$
$\eta_i[n] = \mathbf{t}_i^H[n]\mathbf{t}_i[n]/\mathbf{u}_i^H[n]\mathbf{v}[n]$
$\mathbf{w}_i[n] = \mathbf{w}_{i-1}[n] + \eta_i[n]\mathbf{u}_i[n]$
$\mathbf{t}_{i+1}[n] = \hat{\mathbf{R}}_{xx}[n]\mathbf{w}_i[n] - \hat{\mathbf{r}}_{dx}[n]$
$\Psi_{i+1}[n] = \mathbf{t}_{i+1}^H[n]\mathbf{t}_{i+1}[n]/\mathbf{t}_i^H[n]\mathbf{t}_i[n]$
$\mathbf{u}_{i+1}[n] = -\mathbf{t}_{i+1}[n] + \Psi_i[n]\mathbf{u}_i[n]$

Hybrid per-sample CG.

- Key feature of per sample update CG-MWF $\Rightarrow$ amenability to "smart" initialization
- equalization example: employ semi-blind (training sequence plus signal properties) estimate of propagation channel to form initial estimate of both $\mathbf{R}_{xx}$ and $\mathbf{r}_{dx}$
- then weighted running estimate of $\mathbf{R}_{xx}$ and weighted decision directed updating of $\mathbf{r}_{dx}$
- not possible with RLS since it recursively updates $\mathbf{R}_{xx}^{-1} \Rightarrow$ how to "smartly" initialize $\mathbf{R}_{xx}^{-1}$???

Table 1. "Smart" Initialization of Direct CG

Chan	Path 2			Path 3			Path 4		
	Delay	Gain	Phase	Delay	Gain	Phase	Delay	Gain	Phase
1	19.4	-6.45	291.2	176.7	-0.97	303.5	228.1	-0.28	245.0
2	-13.8	-7.98	146.8	84.9	-2.39	285.2	220.2	-5.59	342.8
3	-27.2	-13.86	91.5	68.8	-4.97	289.0	197.7	-4.67	182.5
4	8.9	-8.33	328.3	25.6	-4.99	299.1	26.8	-1.67	0.8

Table 2. Delays, gains (dB), and phases of the paths relative to main path of four simulated channels including power of all four interfering paths, SNR = 25 dB.

A plot of the channel estimate obtained at an SNR of 25 dB from the running correlator output for a particular run of Channel 1 is overlaid on top of the true channel in Figure 1. Note that because complex pulse shaping is employed in 8-VSB based Digital TV (for purposes of bandwidth efficiency), the channel is complex, having both a real and imaginary part.

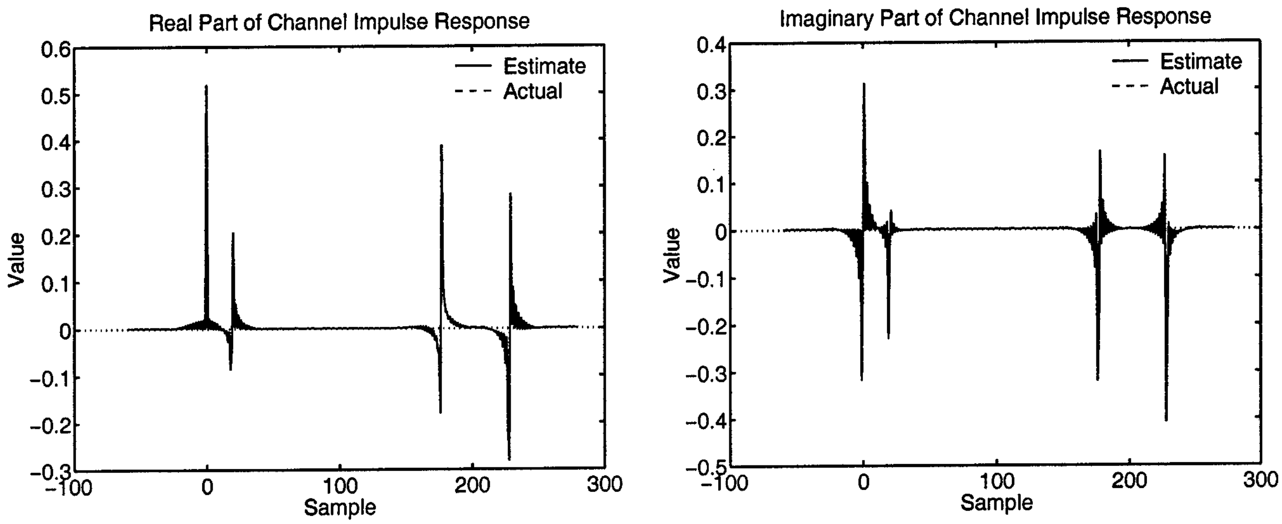

Figure 1. True and estimated and channel impulse responses at an SNR of 25 dB.

Figure 2 displays the learning curves for a Direct CG-MWF based DFE obtained with the various initializations schemes listed below. Each learning curve was obtained by averaging over many Monte Carlo runs for each of the four different channels listed in Table 2. The learning curve obtained with RLS under the same conditions is also plotted. For initialization schemes labeled D and E, all autocorrelation matrices, cross-correlation matrices, and cross-correlation vectors for the CG-MWF based DFE were initialized with the channel estimate obtained from the running correlator output used to locate the training sequence. In scheme D the DFE weight vector was initialized to all zeros except for a one at the cursor location, while in scheme E the feedback taps were initialized with the negative of the post-cursor channel; This yielded a negligible difference in performance. For both schemes D and E and RLS, the feedback register was filled with 448 known symbols thereby effectively reducing the amount of training (per frame) in the 8-VSB system from 704 symbols to 256 symbols. However, note that since RLS was not even close to convergence at 256 symbols, these simulations were run with continuous training to see how long it would take RLS to converge (even with continuous training). The convergence obtained with CG-MWF for initialization schemes D and E was so rapid that a zoom-in of each of these two respective learning curves is plotted in Figure 3. It is observed that convergence is achieved in less than 50 symbols! The channel estimate was of sufficiently high quality that initialization with the channel estimate yielded a convergence nearly identical to that using the true channel.

Various Initialization Schemes for CG-MWF based DFE

A. *Minimal initialization.* Only set one tap equal to unity, all other taps to zero. All matrices and vectors initialized to zero.

B. *Matrix initialization.* In this case, we initialize the correlation matrices using the channel estimate and estimated noise variance N_0.

C. *Feedback tap initialization.* Here, we fill the feedback taps with training symbols prior to beginning adaptation. The correlation matrices are not initialized using the channel.

D. *Matrix and feedback tap initialization.* This is a combination of cases B and C. We initialize the matrices using the estimated channel and noise variance, and we fill the feedback taps with training symbols.

E. *Matrix and feedback tap initialization with equalizer tap weight initialization.* This case is identical to case D except, in addition, we provide a simple initialization of the equalizer tap weights using the negative of the post-cursor portion of the estimated channel.

We make the following observations regarding these performance curves:

"Smart" Initialized CG-DFE versus RLS-DFE:

- *Orders of magnitude difference between convergence time of RLS and convergence time of CG-MWF DFE with "smart" initialization of all correlation matrices, cross-correlation matrices, and cross-correlation vectors.*
- RLS takes over 3000 symbols to converge while "smart" initialized CG-MWF takes less than 50 symbols to converge!
- RLS cannot exploit "smart" initialization since it works on the inverse of the correlation matrix
- Using the aforementioned efficient FFT based processing, no matrices need to be formed with CG-MWF approach
- *dramatic reduction in BOTH convergence time AND computational complexity!*

Finally, we conclude with delineating a number of advantages of CG-MWF based adaptive filtering over RLS based adaptive filtering:

Advantages of CG-MWF over RLS

- CG-MWF implicitly effects reduced-rank adaptive filtering thereby offering performance benefits over RLS under low sample support conditions
- CG-MWF works on $\mathbf{R}_{xx}$ directly $\Rightarrow$ RLS implicitly/explicitly works on $\mathbf{R}_{xx}^{-1}$
- CG-MWF can take advantage of initial estimate of $\mathbf{R}_{xx}$; e.g., formed while searching for training sequence or from channel estimate formed simply from correlation performed to detect training sequence
- CG-MWF can exploit Toeplitz structure of $\mathbf{R}_{xx}$ to use FFT's for reduced computational complexity ($\mathbf{R}_{xx}^{-1}$ is not generally Toeplitz if $\mathbf{R}_{xx}$ is Toeplitz)
- CG-MWF can work with a weighted combination of an $\mathbf{R}_{xx}$ estimated directly from data and an $\mathbf{R}_{xx}$ formed from parametric model
- CG-MWF is not incommensurate with Principal Components $\Rightarrow$ can apply CG-MWF in a space spanned by principal eigenvectors for further rank reduction

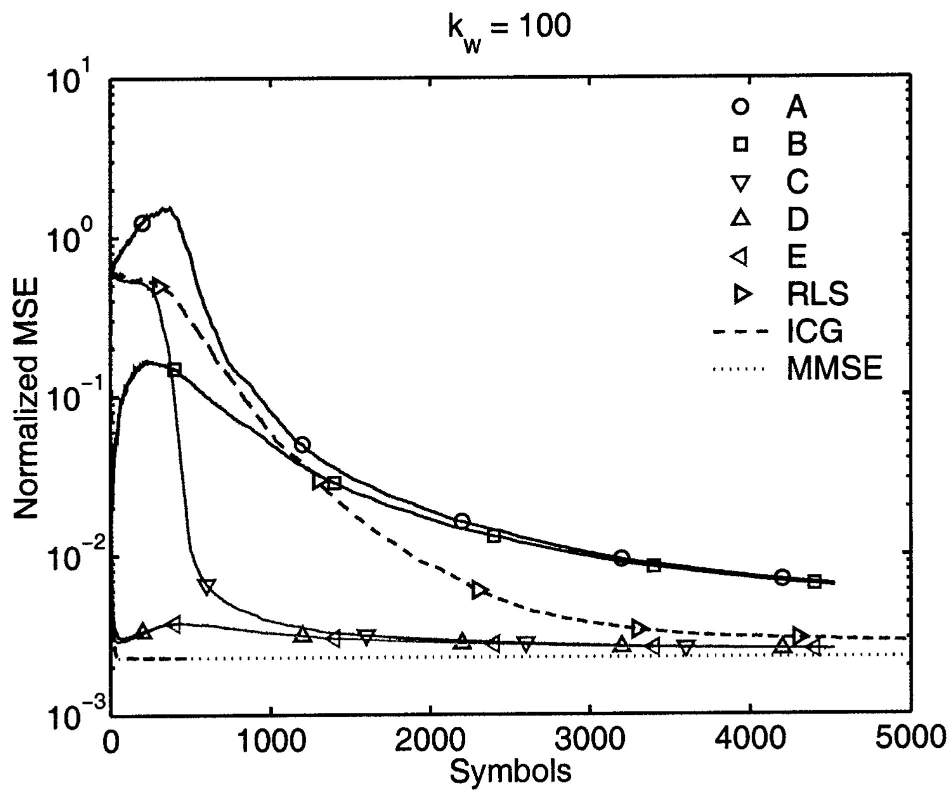

Figure 2. DFE Learning Curves for CG-MWF with Various Initializations

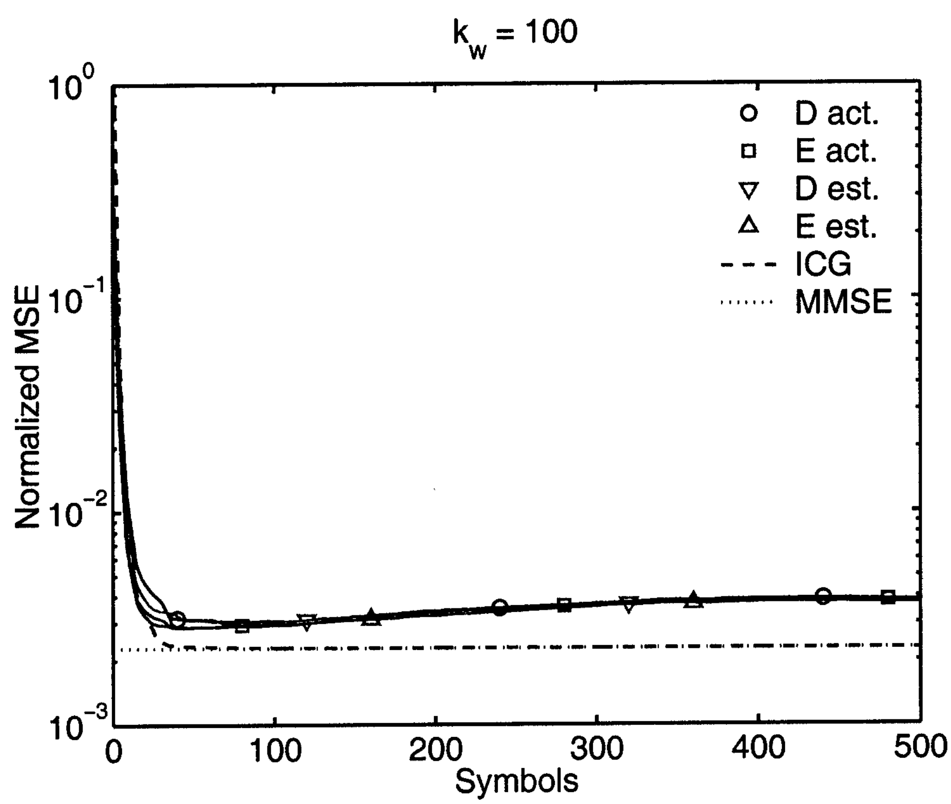

Figure 3. Zoomed-In DFE Learning Curves for CG-MWF

3.4 ADDITIONAL ACCOMPLISHMENTS/NEW FINDINGS

The first year effort focused on the forward link in a high-speed CDMA based multi-user communication system experiencing frequency dependent multipath fading. The mobile handset was assumed to have two antennas, either spatially separated or having diverse polarizations. The downlink specific structure involves first inverting the multipath channel to restore the synchronous multi-user signal transmitted from the base-station at the chip-rate, and then correlating with the product of the desired user's channel code times the base-station specific scrambling code once per symbol to decode the symbols. Our formulation generalizes for the multi-channel case as might be derived from multiple antennas and/or over-sampling with respect to the chip-rate. The optimal symbol-level MMSE equalizer was derived and demonstrated to slightly out-perform the chip-level MMSE equalizer but at a greater computational cost. An MMSE soft hand-off receiver was also derived and simulated. Average BER for a class of multi-path channels was assessed under varying operating conditions of single-cell and edge-of-cell, coded and un-coded BPSK data symbols, and uncoded 16-QAM. These simulations indicate large performance gains compared to the RAKE receiver, especially when the cell is fully loaded with users. Bit error rate (BER) performance for the chip-level equalizers was demonstrated to be well predicted by approximate SINR expressions and a Gaussian interference assumption.

One fundamental question this work tries to address is whether adding a second antenna at the mobile is worth the associated costs and difficulties. In future military communication systems, the physical link from base-station tomobile data terminal will be a major bottleneck. Employing spatial diversity through multiple antennas at the hand-held military radio can help to eliminate this bottleneck. There is great hesitation to include multiple antennas on the hand-held military radio because of the extreme pressures to keep low power and low weight. However, the cost of bandwidth is also competing head-on. Our simulations show the great potential a multiple antenna equalizer has for reducing interference and hence increasing system performance, range and capacity. Broadband wireless access will require exponential increases in system performance, so we believe it is only a matter of time before the idea of two or more antennas at a hand-set is embraced by the military and put into practice.

3.5 Key Simulation Results

As an illustrative example, a high-speed CDMA **forward link** was simulated. The chip rate was 3.6864 MHz ($T_c = 0.27\mu s$). Simulations were performed for a "saturated cell": all channel codes were "active" with equal power. For each user, each BPSK data symbol was spread with one of 64 Walsh-Hadamard sequences of length 64. Due to the frequency selective nature of the multipath channel in a high-speed (wideband) 3G CDMA link, the advantage of employing orthogonal Walsh-Hadarmard sequences relative to avoiding multi-user access interference is destroyed and the RAKE receiver performs poorly, especially in a saturated case. Chip-level equalization is thus effected at the receiver in order to estimate the synchronous sum signal transmitted from the base station and thereby effectively exploit the orthogonality of the Walsh-Hadamard codes.

All users were of equal power, and their signals were summed synchronously and then multiplied with a QPSK scrambling code of length 32678. The channels were modeled to have four equal-power multi-paths, the first one arriving at 0, the last at $10\mu s$ (corresponding to about 37 chips) and the other two delays picked at random in between. The multipath coefficients are complex normal, independent random variables with equal variance. The receiver was assumed to have a dual antenna. The arrival times at antenna 1 and 2 are the same, but the multipath coefficients are independent.

In the two base-station case, the channels are scaled so that the total energy from each of the two base-stations is equal at the receiver. The 4 multi-path arrivals from the 2nd base-stations are random, with maximum delay spread of $10\mu s$. SNR is defined to be the ratio of the sum of the average power of the received signals over all the channels, to the average noise power, after chip-matched filtering. The abscissa is the **post**-correlation SNR for *each* user which includes a processing gain of $10\log(64) \approx 18$ dB.

Figure 1 plots the Mean-Square Error for the different reduced-rank methods as a function of the subspace dimension, D. The channel statistics and noise power are assumed to be known (i.e. perfect channel estimation). In the single base-station case, 1(a), the dimension of the full space is 114 (the equalizer length is 57 at each of 2 antennas, as multipath delay spread is 37 chips and the chip pulse waveform is cut off after 5 chips at both ends). The MSE for MSNWF is seen to drop dramatically with D, and achieves the performance of the full-rank Wiener filter at dimension approximately 7! In contrast, the dimensionality required for Principal Components method to achieve near optimum MMSE is more than twice the delay spread, and the required dimensionality for the Cross-spectral method is also high.

Figure 2(a) displays the BER curves obtained with the MSNWF for different sizes of the reduced-dimension subspace. The channel statistics are assumed to be known perfectly, so these curves serve as an informative upper bound on the performance. It is observed that even a 2-stage reduced-rank filter outperforms the RAKE at all SNR's and only a small number of stages of the MSNWF are needed in order to achieve near full-rank MMSE performance over a practical range of SNR's.

Figures 1(b) and 2(b) display similar plots, but for the "edge of cell" scenario corresponding to soft hand-off. Here we effect 4 channels at the receiver by sampling the received signal at twice the chip-rate at each antenna. The dimension of the full space is 228 which makes full rank processing quite cumbersome. Amazingly, the MSE for MSNWF still goes down very steeply with rank and achieves the full-rank value for a subspace dimension of only 8. In Figure 2(b), the bit error is plotted for the "soft handoff" mode. With perfect channel estimation, the MSNWF can achieve uncoded BER's similar to the full-rank MMSE over a practical SNR range after stopping at stage as low as 5!

These plots suggest that MSNWF can achieve rapid adaptation in the case where the chip-level MMSE equalizer is adapted based on a pilot channel. Figure 3 plots the output SINR for different chip-level equalizers vs. time in symbols, at a fixed SNR. The MSNWF at stages 5 and 10 yields very good performance with low sample-support. The convergence rate is significantly better than that of full-rank RLS which even asymptotically does not beat the MSNWF of rank only 10! The LMS algorithm converges much more slowly. For the two base-station case, the asymptotic SINR is lower for all the equalizers due to the added interference from the MAI of the 2nd base-station. But the convergence speed of the low-rank MSNWF is still impressive. The BER curves in Figure 8 illustrate the performance of these equalizers. Note that graphs presented plot uncoded BER. In practice, the target uncoded BER is somewhere between 10^{-1} and 10^{-2}. Figure 8 (a) reveals that for uncoded BER's in this range, the stage 5 MSNWF performs better than the stage 10 or stage 15 MSNWF, as well as better than full-rank RLS! This improvement comes with dramatically lower computational complexity than RLS. The LMS algorithm is simpler, but performs extremely poor with slow convergence.

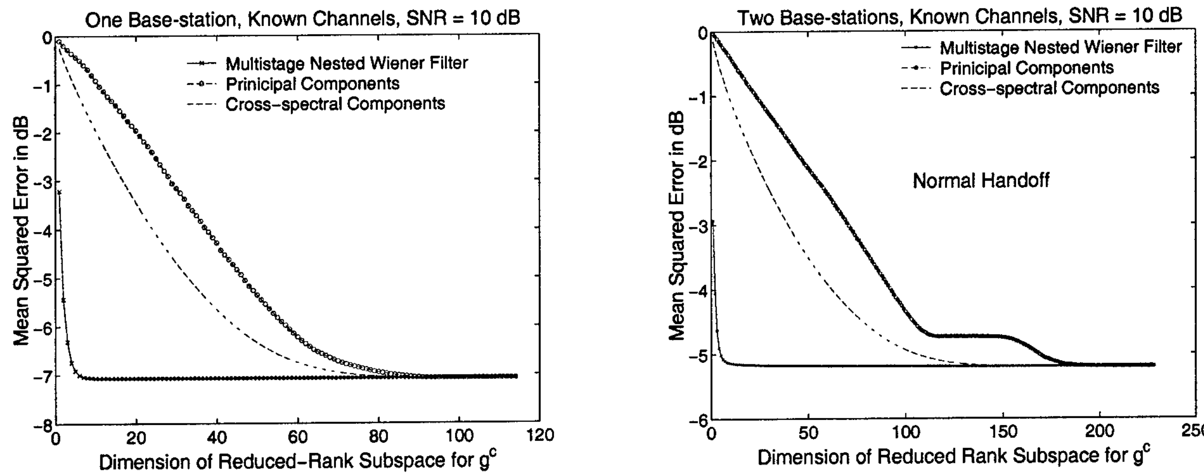

Figure 1: MSE vs Rank of Reduced Dimension Subspace

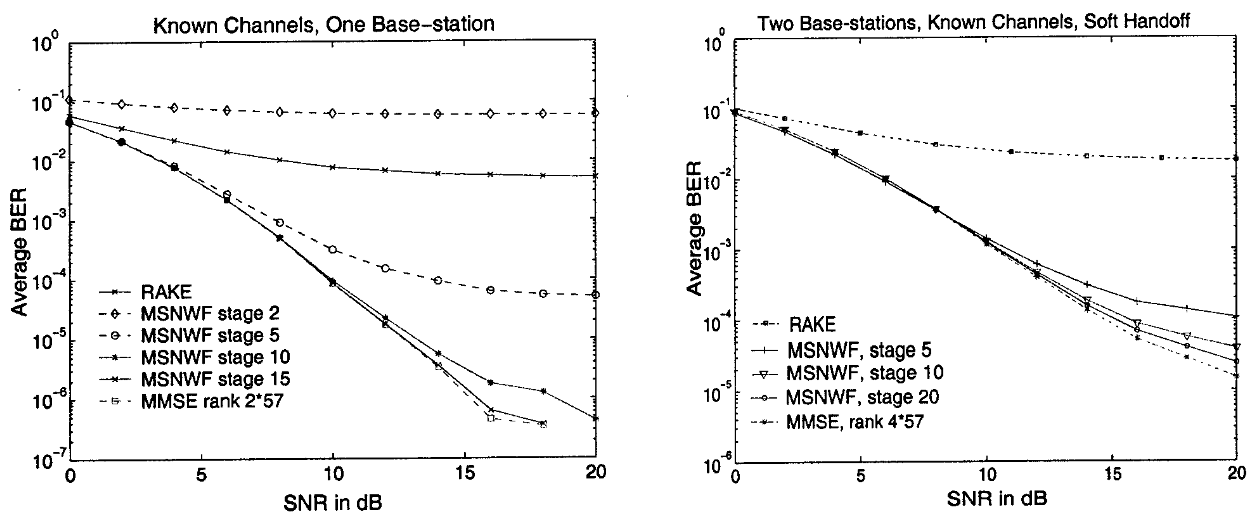

Figure 2: BER for Different Chip-level Equalizers for CDMA Downlink.

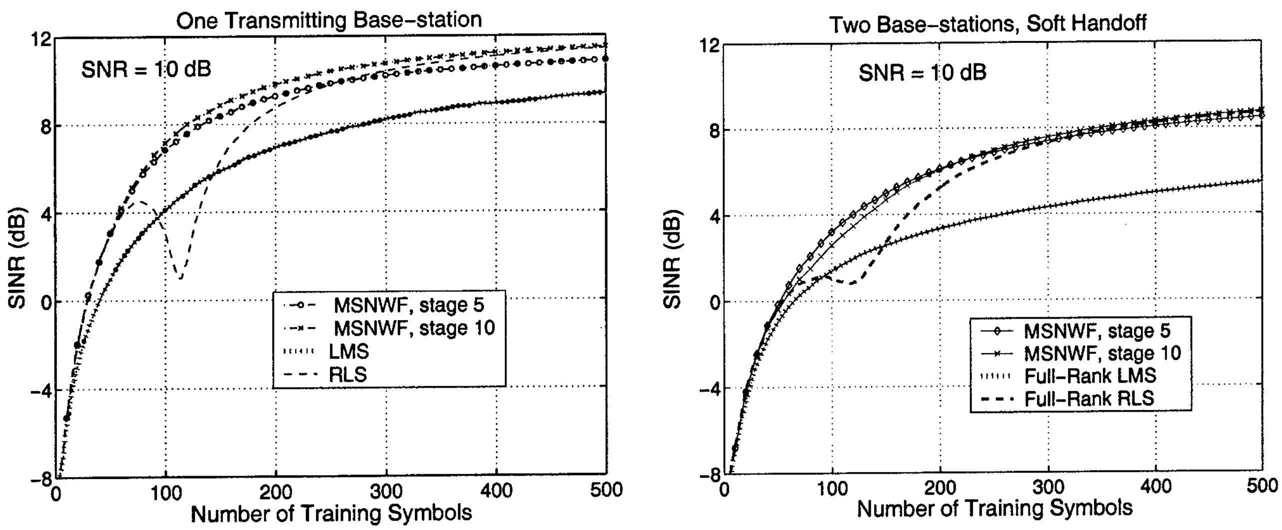

Figure 3: Output SINR vs Time for Adaptive Chip-level Equalizers for CDMA downlink.

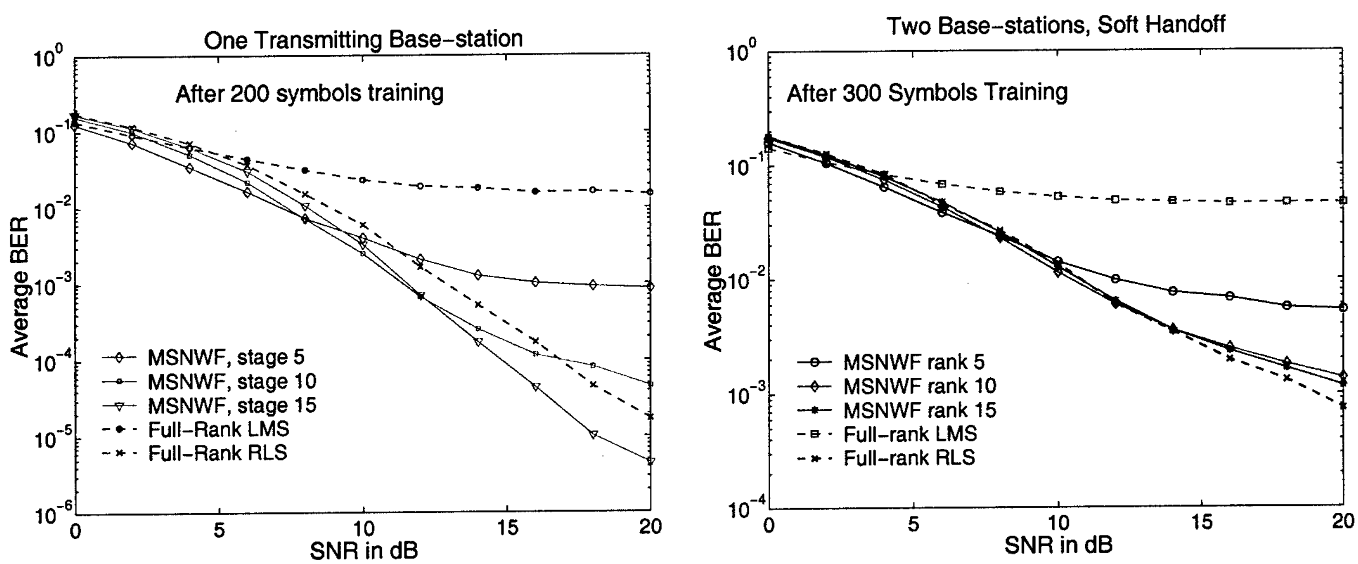

Figure 4: BER for Adaptive Chip-level Equalizers for CDMA Downlink.

4 PERSONNEL SUPPORTED

Faculty:	Michael D. Zoltowski (PI)
Graduate Students:	Samina Chowdhury

5 PUBLICATIONS

5.1 Journal Papers Published and/or Accepted

1. T. Krauss and M. D. Zoltowski, "Multiuser Second-Order Statistics Based Blind Channel Identification for Using a Linear Parameterization of the Channel Matrix," *IEEE Trans. on Signal Processing,* vol. 48, no. 9, September 2000, pp. 2473-2486.

2. K. T. Wong and M. D. Zoltowski, "Self-Initiating MUSIC Based Direction Finding in Polarized Beamspace," *IEEE Transactions on Antennas and Propagation,* vol. 48, no. 8, August 2000, pp. 1235-1245.

3. Murat Torlak, Hui Liu, and M. D. Zoltowski, "OFDM Blind Carrier Offset Estimation: ESPRIT," *IEEE Transactions on Communications,* vol. 48, Sept. 2000, pp. 1459-1461.

4. Anand Kannan, T. Krauss, and M. D. Zoltowski, "Separation of Co-channel Signals Under Imperfect Timing and Carrier Synchronization," *IEEE Transactions on Vehicular Technology,* vol. 50, Jan. 2001, pp. 79-96.

5. P. Tichavsky, K. T. Wong and M. D. Zoltowski, "Near-Field/Far-Field Azimuth and Elevation Angle Estimation Using a Single Vector Sensor," *IEEE Transactions on Signal Processing,* vol. 49, no. 11, November 2001, pp. 2498-2510.

6. T. Krauss, W. Hillery, and M. D. Zoltowski, "Downlink Specific Linear Equalization for Frequency Selective CDMA Cellular Systems," **Journal of VLSI Signal Processing, Special Issue on Signal Processing for Wireless Communications: Algorithms, Performance, and Architecture,** Vol. 30, Nos. 1-3, January-March 2002, pp. 143-162.

7. S. Chowdhury, M. D. Zoltowski, and J. S. Goldstein, "Reduced-Rank Chip-Level MMSE Equalization for the 3G CDMA Forward Link with Code-Multiplexed Pilot," **EURASIP Journal on Applied Signal Processing Special Issue on 3G Wireless Communications and Beyond,** Vo. 2002, No. 8, August 2002, pp. 771-786.

8. Tai-Ann Chen, M. P. Fitz, S. Li, and M. D. Zoltowski, "Two Dimensional Space-Time Pilot Symbol Assisted Demodulation for Frequency Nonselective Rayleigh Fading Channels," accepted for publication in *IEEE Transactions on Communications*, by Dr. Xiaodai Dong, Editor for Modulation & Signal Design, 18 June 2002.

5.2 Conference Papers Published and/or Accepted

1. Thomas P. Krauss and Michael D. Zoltowski, "MMSE Equalization for Saturated 3G CDMA Systems with OVSF Channel Codes and Frequency Selective Multipath," *invited paper, Proc. 2000 Conference on Information Sciences and Systems (CISS2000),* Princeton, NJ, pp. TP-3, March 15-17, 2000.

2. Thomas P. Krauss and Michael D. Zoltowski, "Oversampling diversity versus dual antenna diversity for chip-level equalization on CDMA downlink," *First IEEE Sensor Array and Multichannel Signal Processing Workshop,* Cambridge, Massachusetts, 16-17 March 2000.

3. Thomas P. Krauss and Michael D. Zoltowski, "Chip-Level MMSE Equalization for High-Speed Synchronous CDMA in Frequency Selective Multipath," *SPIE's International Symposium on AeroSense,* Orlando, Florida, **SPIE Proceedings Volume 4045: Digital Wireless Communications**, 27-28 April 2000, pp.187-197.

4. Thomas P. Krauss and M. D. Zoltowski, "Simple MMSE Equalizers for CDMA Downlink to Restore Chip Sequence: Comparison to Zero-forcing and RAKE," *Proc. of 2000 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Istanbul, Turkey, vol, V, pp. 2865-2868, 5-9 June 2000.

5. Thomas Hong Li and M. D. Zoltowski, "Semi-Blind Channel Identification for W-CDMA by Orthogonal Transmit Diversity," *Proc. of 2000 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Istanbul, Turkey, vol. V, pp. 2861-2864, 5-9 June 2000.

6. Wilbur Myrick and M. D. Zoltowski, "Exploiting Conjugate Symmetry in Power Minimization Based Pre-Processing for GPS: Reduced Complexity and Smoothness," *Proc. of 2000 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Istanbul, Turkey, vol. V, pp. 2833-2836, 5-9 June 2000.

7. Michael D. Zoltowski, "Space-Time Equalization for Forward Link in 3G CDMA," *Digital Signal Processing Systems (DSPS Fest 2000)*, Houston, TX, 2-4 August 2000.

8. Samina Chowdhury, Michael D. Zoltowski, and Scott Goldstein, "Reduced-Rank Adaptive MMSE Equalization for the Forward Link in High-Speed CDMA," *invited paper, 43rd IEEE Midwest Symposium on Circuits and Systems*, East Lansing, MI, 8-11 August 2000.

9. Wilbur Myrick, M. D. Zoltowski, and J. S. Goldstein, "GPS Jammer Suppression with Low-Sample Support Using Reduced-Rank Power Minimization," *Proc. of the 10th IEEE Workshop on Statistical Signal and Array Processing, SSAP 2000,* Pocono Manor, PA, 14-16 August 2000, pp. 514-518.

10. Thomas P. Krauss, William J. Hillery, and M. D. Zoltowski, "MMSE Equalization for Forward Link in 3G CDMA: Symbol- Level Versus Chip-Level," *Proc. of the 10th IEEE Workshop on Statistical Signal and Array Processing, SSAP 2000,* Pocono Manor, PA, 14-16 August 2000, pp. 18-22.

11. Thomas P. Krauss and Michael D. Zoltowski, "MMSE Equalization Under Conditions of Soft Hand-Off," *IEEE Sixth International Symposium on Spread Spectrum Techniques & Applications (ISSSTA 2000)*, Parsippany, NJ, 6-8 September 2000, pp. 540-544 **Winner of Best Paper Award.**

12. Wilbur Myrick, M. D. Zoltowski, and J. S. Goldstein, "Low-Sample Performance of Reduced-Rank Power Minimization Based Jammer Suppression for GPS," *IEEE Sixth International Symposium on Spread Spectrum Techniques & Applications (ISSSTA 2000)*, Parsippany, NJ, 6-8 September 2000, pp. 93-97.

13. Tom Hong Li and Michael D. Zoltowski, "Paired Semi-Blind Channel Identification for Wideband CDMA Communications," *IEEE Sixth International Symposium on Spread Spectrum Techniques & Applications (ISSSTA 2000)*, Parsippany, NJ, 6-8 September 2000, pp. 301-304.

14. Thomas P. Krauss and M. D. Zoltowski, "Chip-level MMSE Equalization at the Edge of the Cell," *2nd IEEE Wireless Communications and Networking Conference (WCNC 2000)*, Chicago, IL, 23-28 September 2000.

15. Thomas Hong Li and M. D. Zoltowski, "Semi-Blind Channel Identification for W-CDMA by Orthogonal Transmit Diversity," *2nd IEEE Wireless Communications and Networking Conference (WCNC 2000)*, Chicago, IL, 23-28 September 2000.

16. W.L. Myrick, M.D. Zoltowski, and J.S. Goldstein, "Adaptive Anti-Jam Reduced-Rank Space-Time Preprocessor Algorithms for GPS," *Institute of Navigation (ION) Conference,* Salt Lake City, Utah, 17-20 Sept. 2000.

17. Samina Chowdhury, Michael D. Zoltowski, and J. Scott Goldstein, "Application of Reduced-Rank Chip-Level MMSE Equalization to Forward Link DS-CDMA with Frequency Selective Multipath," *Proceedings 38th Annual Allerton Conference on Communications, Systems, and Computing,* 4-6 Oct. 2000.

18. H.E. Witzgall, J.S. Goldstein and M.D. Zoltowski, "A non-unitary extension to spectral estimation," accepted for *The Ninth IEEE Digital Signal Processing Workshop* Hunt, Texas, October 15-18, 2000.

19. Michael D. Zoltowski, Samina Chowdhury, and J. Scott Goldstein, "Reduced-Rank Adaptive MMSE Equalization for High-Speed CDMA Forward Link with Sparse Multipath Channels," *invited paper, Conf. Record of the 34th Asilomar IEEE Conference on Signals, Systems, and Computers,* 29 Oct. - Nov. 1, 2000.

20. Michael D. Zoltowski and William Hillery, "Comparative Performance Evaluation of Three Symbol-Level MMSE Equalizers for CDMA Forward Link in Frequency Selective Multipath," *invited paper, Conf. Record of the 34th Asilomar IEEE Conference on Signals, Systems, and Computers,* 29 Oct. - Nov. 1, 2000.

21. H.Witzgall, J.S.Goldstein, M.Zoltowski, S.Huang and I.S.Reed, "ROCK MUSIC: A Reduced Order Correlation Kernal extension of the MUSIC algorithm," *invited paper, Conf. Record of the 34th Asilomar IEEE Conference on Signals, Systems, and Computers,* 29 Oct. - Nov. 1, 2000.

22. Michael D. Zoltowski, M. Joham, and S. Chowdhury, "Recent Advances in Reduced-Rank Adaptive Filtering with Applications to High-Speed Wireless Communications," (Keynote Address), *SPIE's International Symposium on AeroSense,* Orlando, Florida, **SPIE Proceedings Volume 4395: Digital Wireless Communications III**, 17-18 April 2001, pp. 1-16.

23. Michael D. Zoltowski, G. Dietl, M. Joham, "Recursive reduced-rank adaptive equalization for wireless communications," *SPIE's International Symposium on AeroSense,* Orlando, Florida, **SPIE Proceedings Volume 4395: Digital Wireless Communications**, 17-18 April 2001.

24. Wilbur Myrick, M. D. Zoltowski, and J. S. Goldstein, "Low Complexity Anti-Jam Space-Time Processing for GPS," *Proc. of 2001 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Salt Lake City, 7-11 May 2001.

25. S. Chowdhury, M. D. Zoltowski, and J. S. Goldstein, "Structured MMSE Equalization For Synchronous CDMA with Sparse Multipath Channels," *Proc. of 2001 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Salt Lake City, 7-11 May 2001.

26. S. Chowdhury and M. D. Zoltowski, "Structured MMSE Equalization," *IEEE CAS-Notre Dame Workshop on Wireless Communications and Networking*, University of Notre Dame, 9-10 August 2001.

27. S. Ozen, M. Fimoff, M. D. Zoltowski, and W. Hillery, "Using the Result of 8-VSB Training Sequence Correlation as a Channel Estimate for DFE Tap Initialization," *Proceedings 39th Annual Allerton Conference on Communications, Systems, and Computing,* 4-6 Oct. 2001.

28. Guido Dietl and Michael D. Zoltowski, "Reduced-Rank Equalization for EDGE Via Conjugate Gradient Implementation of Multi-Stage Nested Wiener Filter," *IEEE Vehicular Technology Conference (VTC) 2001,* Atlantic City, NJ, 7-11 October 2001.

29. S. Chowdhury and Michael D. Zoltowski, "Application of Conjugate Gradient Methods in MMSE Equalization for the Forward Link of DS-CDMA," *IEEE Vehicular Technology Conference (VTC) 2001,* Atlantic City, NJ, 7-11 October 2001.

30. M. D. Zoltowski, M, Joham, J. S. Goldstein, and M. Honig, "A New Backward Recursion for the Multi-Stage Nested Wiener Filter Employing Krylov Subspace Methods," *IEEE Military Communications (MILCOM 2001)*, Vienna, VA, 28-31 Oct. 2001.

31. Samina Chowdhury and Michael D. Zoltowski, "Combined MMSE Equalization and Multi-User Detection for High-Speed CDMA Forward Link with Sparse Multipath Channels," *Conf. Record of the 35th Asilomar IEEE Conf. on Signals, Systems, and Computers*, pp. 389-393, 4-7 November 2001.

32. S. Chowdhury and M. D. Zoltowski, "Conjugate Gradient Based MMSE Equalization for DS-CDMA Forward Link in Time-varying Frequency Selective Channels," *IEEE Globecom 2001*, San Antonio, Texas, 25-29 November 2001.

33. M. D. Zoltowski, W. J. Hillery, S. Ozen, and M. Fimoff, "Conjugate-gradient-based decision feedback equalization with structured channel estimation for digital TV," *SPIE's International Symposium on AeroSense*, Orlando, Florida, **SPIE Proc. Vol. 4740: Digital Wireless Communications**, 1-4 April 2002, pp. 95-105.

34. S. Chowdhury and M. D. Zoltowski, "Adaptive MMSE Equalization for Wideband CDMA Forward Link with Time-varying Frequency Selective Channels," *Proc. of 2002 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Orlando, FL, 13-17 May 2002.

35. Michael Zoltowski, William Hillery, Serdar Ozen, and Mark Fimoff, "Conjugate Gradient Based Multichannel Decision Feedback Equalization for Digital Television," *Second IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2002)*, Rosslyn, VA, 5-6 August 2002.

36. Serdar Ozen and Michael Zoltowski, "A Novel Structured Channel Estimation Method for Sparse Channels with Applications to Multi-Antenna Digital TV Receivers," *Second IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2002)*, Rosslyn, VA, 5-6 August 2002.

37. Matthew Weippert, John Hiemstra, J. Scott Goldstein, and Michael Zoltowski, "Insights from the Relationship Between the Multistage Wiener Filter and the Method of Conjugate Gradients," *Second IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2002)*, Rosslyn, VA, 5-6 August 2002.

38. Michael Zoltowski, "Conjugate Gradient Based Adaptive Filtering with Application to Space-Time Processing for Wireless Communications," **Distinguished Lecture,** *Second IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2002)*, Rosslyn, VA, 5-6 August 2002.

39. S. Ozen, W. Hillery, M. D. Zoltowski, S.M. Nerayanuru, and M. Fimoff, "Structured Channel Estimation Based Decision Feedback Equalizers for Sparse Multipath Channels with Application to Digital TV Receivers," *Conf. Record of the 36th Asilomar IEEE Conf. on Signals, Systems, and Computers*, Asilomar, CA, 3-6 November 2002.

40. G. Dietl and M. D. Zoltowski, "Multi-Stage MMSE Decision Feedback Equalization for EDGE," *Proc. of 2003 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Hong Kong, 6-10 April 2003, Vol. IV, pp. 413-416.

6 INTERACTIONS/TRANSITIONS:

6.1 A. Participation/presentations at meetings, conferences, seminars, etc

- Attended the *2002 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing* held during 7-11 May 2001 in Salt Lake City, Utah. In conjunction with this conference, the following functions were performed:

- reviewed 25 submitted paper summaries a-priori.
- presented two technical papers relating research supported by this grant
- attended a meeting of the Communications Technical Committee as an elected member
- attended a meeting of the Sensor Array and Multichannel Technical Committee as an elected member

- see conference papers listed in Section 5.2
- Conference Co-Chair, Symposium on Digital Wireless Communications III, AEROSENSE: Aerospace/Defens Sensing, Simulation and Controls, Orlando, FL, 17-18 April 2001.

6.2 B. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories

- Served on review panel for National Science Foundation, Signal Processing Systems (SPS) Regular Panel Review, CISE Directorate, Communications and Computing Research (CCR), Davis, CA, 21-22 February 2002.
- Served on review panel for National Science Foundation, Samll Information Technology Research (ITR) Panel Review, CISE Directorate, Computing and Communications Research Program, Arlington, VA, 5-6 June 2002.

6.3 C. Transitions

An all-day tutorial entitled "TUTORIAL ON REDUCED-RANK ADAPTIVE FILTERING BASED ON THE MULTI-STAGE WIENER FILTER" was presented on 18 June 2002 to the CITE Group at Rome Labs headed by Dr. Bruce Suter. Dr. Bruce Suter and CITE will implement and assess the performance of the Conjugate-Gradient based reduced rank filtering schemes developed as part of this project. We will continue to report of this ongoing transition as it progresses.

7 NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

Plan to file patent disclosureson Fast FFT-based implementation of Conjugate-Gradient based reduced rank filtering during the Fall 2001. New discoveries and inventions summarized previously.

8 HONORS/AWARDS

1. **2002 Technical Achievement Award of IEEE Signal Processing Society.** http://www.ieee.org/organ , "The Technical Achievement Award honors a person who, over a period of years, has made outstanding technical contributions to the theory and/or practice in technical areas within the scope of the Society, as demonstrated by publications, patents, or recognized impact on the field. The prize shall be $1500, a plaque and a certificate, and shall be presented at the ICASSP meeting held during the Spring following selection of the winner."
2. **Leonard G. Abraham Prize Paper Award in the Field of Communications Systems, IEEE Communications Society**, recipient along with Tai-Ann Chen, Wen-Yi Kuo, Jim Grimm, and Michael P. Fitz, for "A Space-Time Model for Frequency Nonselective Rayleigh Fading Channels with Applications to Space-Time Modems" appearing in the July 2000 issue of IEEE Journal on Selected Areas in Communications (Vol. 18, No. 7, pp. 1175-1190). Award

presented at IEEE International Communications Conference (ICC) in Helsinki, Finland, on June 13, 2001. http://www.comsoc.org/socstr/awards/paperawards.html http://www.comsoc.org/socstr/awards/paperawards.html#Leonard G. Abraham Prize

3. **2003 Distinguished Lecturer for IEEE Signal Processing Society.** There are six Distinguished Lecturers chosen each year to represent the Society by giving lectures on their research around the world. The web site for the SPS Distinguished Lecturer Program http://www.ieee.org/organizatic indicates that "The Society's Distinguished Lecturer Program provides means for chapters to have access to individuals who are well known educators and authors in the fields of signal processing, to lecture at Chapter meetings."

4. **Best Paper Award at IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA 2000)**, recipient along with Thomas P. Krauss, held in Parsippany, NJ, 6-8 September 2000. The paper was entitled "MMSE Equalization Under Conditions of Soft Hand-Off."

5. **University Faculty Scholar**, Purdue University, $50K award plus plaque. Two faculty members selected from engineering per year. 1 August 2000-31 July 2004.

6. **Distinguished Lecturer** for *2002 IEEE Sensor Array and Multichannel (SAM) Workshop* in Rosslyn, VA, on 4-6 August 2002. One of 11 researchers invited to present Distinguished Lecture. http://ite.gmu.edu/sam2002/distinguished_lecturers.htm

7. **Advisory Council for the Department of Electical and Computer Engineering at Drexel University.** August 2002-present. First meeting attended on 3 December 2003. Also, highlight article in Drexel University's (1) 2003 College of Engineering Brochure, (2) Spring 2003 Electrical and Computer Engineering (ECE) Newsletter, and (3) ECE Web Page's Alumni News Section.